A photon signal from stimulated decays of axion dark matter in the Milky Way

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QCD axions and ALPs - motivation

• QCD axions solve the strong CP problem

\[ \mathcal{L}_{\text{QCD}} \supset - \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \theta \]

(ALPs: let \( m_a \) and \( f_a \) be independent parameters)

theory: \( \theta = \text{arbitrary} \)

experiment: \( |\theta| \lesssim 10^{-10} \)

C. Abel et al. 2001.11966

• possible candidates for dark matter

L. F. Abbott & P. Sikivie (1983) …

• explain astrophysical anomalies:
  • Stellar cooling
  • TeV gamma-ray transparency
  • Hard X-ray from neutron stars

G. G. Raffelt et al. 1110.6397
M. Giannotti et al. 1512.08108
K. Kohri & H. Kodama 1704.05189
G. Galanti et al. 2210.05659
Malte Buschmann et al. 1910.04164

E. Witten (1984), D. Chung et al. 0009292, B. Bellazzini et al. 1702.02152

• string theory, \((g - 2)_\mu\) problem, R-parity breaking … etc.
Axion searches

haloscopes & helioscopes

CAST
IAXO
ADMX
ALPS
MADMAX
...

beam dump experiments & coliders

BaBar
E137
E141
CHARM
LEP
...

GRB
Sun
Globular Cluster
NS, WD, SN
Polarizations
...

astrophysics

CMB spectra
birefringence
D & He abundance
X-ray background
...

cosmology

Image: CAST collaboration
Image: BaBar collaboration
Image: J.H. Buckley et al. 2004.06486
Image: Planck collaboration
• axion-like particle dark matter in the Galaxy

• $m_a \simeq 0.1 - 100 \, \mu\text{eV}$

• coupled only to a photon: $\mathcal{L}_{\text{int.}} = -\frac{g_{a\gamma}}{4}a F_{\mu\nu} \tilde{F}^{\mu\nu}$
Stimulated decay of axion

\[ \mathcal{L}_{\text{int.}} = -\frac{g_{\alpha\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Change of a distribution function due to \( a (p_a) \to \gamma (p_1) + \gamma (p_2) \) and the inverse

\[
\frac{d}{dt} f_1 = \frac{1}{2E_1} \int \frac{d^3 p_a}{(2\pi)^3 2E_a} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \left| \mathcal{M} \right|^2 \left( f_a (1 + f_1) (1 + f_2) - f_1 f_2 (1 + f_a) \right) (2\pi)^4 \delta^4 (p_a - p_1 - p_2)
\]

Bose enhancement

stimulated decay of axion \quad axion production from two photons

In the rest frame of axion

background EM field

\[ E_{\gamma} = m_a / 2 \]
Stimulated decay of axion in the Milky Way

Background radio photons stimulate axion decays

electrons in the MW could absorb radio photons

radio photon source (Cygnus A, S147, Vela…)

Counter-image of a bright radio source is expected
Photon signal

\[ S(\nu) = \frac{m_3 g_2^2}{64 \pi} \frac{1}{4 \pi \Delta \nu} \int d\Omega \rho_a(x, \Omega) e^{-\tau(\nu, x, \Omega)} \left( f_\gamma(x, \vec{p}, \Omega, t) + f_\gamma(x, -\vec{p}, \Omega, t) \right) \]

free free absorption
(a free electron gains energy during a collision with an ion by absorbing a photon)

background photons
• CMB
• Extragalactic background

\[ T_{\text{exgal}}(\nu) \approx 1.19 \left( \frac{\text{GHz}}{\nu} \right)^{2.62} \text{K} \]

• photons from galactic source (408MHz Haslam map)
Axion stars

$\rho_a(r)$ ? $\rightarrow$ NFW profile (cuspy) and Burkert profile (cored)

- a clump of axions supported by quantum pressure
- solutions of Klein-Gordon equation + Poisson equation
  + assumptions + simplifications
- $R_a \sim (270 \text{ km}) \left( \frac{10 \mu \text{eV}}{m_a} \right)^2 \left( \frac{10^{-12} M_\odot}{M_a} \right)$

could be modified by a formation of axion stars and their gravitational interactions with normal stars

$\rightarrow \rho_a(r)$ is modified by 10% at most
Signal-to-noise ratio of a single antenna

\[
\frac{S}{N} = \frac{m_\alpha^3 \sigma_\alpha^2}{512 \pi^2} \frac{\eta A f_\Delta}{k_B T} \sqrt{\frac{t_{\text{obs}}}{\Delta \nu}} \int d\mathbf{x} \int d\Omega \rho_a(x, \Omega) e^{-\tau(\nu, x, \Omega)} \left( f_\gamma(x, \mathbf{p}, \Omega, t) + f_\gamma(x, -\mathbf{p}, \Omega, t) \right)
\]
The large signal-to-noise ratio is obtained in
• the direction of the GC and the anti-GC
• the opposite direction to bright radio sources
Detectability

Detectability of photons from a stimulated decay of axions from several directions (Galactic center, anti-Galactic center, S147, W28, W50, Vela) by 100 hrs of observation

$g_{a\gamma} \gtrsim 2 \times 10^{-11} \text{ GeV}^{-1} \ (m_a \approx 10^{-6} \text{ eV})$ produce the radio photon flux detectable at the SKA Observatory
Occupation numbers of photons

\[ v_{\gamma} \text{ [GHz]} \]

\[ 2^f \]

\[ m_a \text{ [eV]} \]

\( \theta < 1 \text{ deg} \)

\( \theta < 0.01 \text{ deg} \)

A. Caputo et al. 1811.08436
**Distribution of ALP**

The NFW profile:

$$\rho_a(r) = \frac{\delta_c \rho_c}{(r/r_s) (1 + r/r_s)^2}$$

$$\delta_c = \frac{\Delta_{\text{vir}}}{3} \frac{r_c^3}{\ln (1 + r_c) - r_c/(1 + r_c)}$$

- \(r_s \simeq 20 \text{ kpc}\) : the scale radius
- \(\Delta_{\text{vir}} = 200\)
- \(R_{\text{vir}} \simeq 221 \text{ kpc}\) : the virial radius
- \(r_c \equiv R_{\text{vir}}/r_s\)

The Burkert profile:

$$\rho(r) = \frac{\rho_s}{\left(1 + \frac{r}{r_{sb}}\right)^2 \left(1 + \frac{r}{r_{sb}}\right)^2}$$

- \(r_{sb} = 12.67 \text{ kpc}\)
Noise

Four contributions to the noise temperature $T$

- atmospheric radio wave $T \sim 3$ K
- CMB $T \sim 2.725$ K
- noise of receiver $T \sim 20,40$ K
- Synchrotron radiation from the Galactic or extragalactic system

$$T_{bg} = 60 \left( \frac{300 \text{MHz}}{\nu} \right)^{2.55} \text{ K}$$
Physics of a scalar field coupled to gravity is described by the action

\[ S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} g^{\mu\nu} \partial_{\mu} \phi \partial_{\nu} \phi - V(\phi) - \frac{1}{16\pi G} R \right] \]

Trick to solve a resulting EoM:

Assuming axion is non-relativistic

\[ \phi(r, t) \approx \frac{1}{\sqrt{2m_a}} \left( \psi(r, t)e^{-im_a t} + \psi^*(r, t)e^{+im_a t} \right) \]

and taking an average over scales larger than \( m_a \)

Gross-Pitaevskii-Poisson equations are obtained

\[ iv = -\frac{1}{2m_a} \nabla^2 \psi + \left[ V'_\text{eff} (\psi^* \psi) + m_a \Phi \right] \psi \]

\[ \nabla^2 \Phi = 4\pi Gm_a \psi^* \psi \]